DETERIORATION OF PARKING STRUCTURES: EXTENT, CAUSES AND REPAIR CONSIDERATIONS

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Policy Development and Research Sector
of
Canada Mortgage and Housing Corporation
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March 31, 1986

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This project was funded by Canada Mortgage and Housing Corporation, but the views expressed are the personal views of the author(s) and no responsibility for them should be attributed to the Corporation.

Acknowledgements:

The author wishes to acknowledge the assistance of the following individuals in the preparation of this document:

Mr. K.H. Thompson (PWC), Dr. G.G. Litvan (DBR, NRC) and Mr. J.A. Bickley (Trow Ltd.) for their review of the document.

Mr. F.E. Plimmer (CMHC) for providing the framework for life cycle cost analyses as well as cost data.

Mr. D. Morgan for the use of a number of photographs which were part of a final year engineering project at Carleton University carried out under the supervision of Dr. Suter.

Mr. D. O'Neal (Ottawa Structural Concrete Services Ltd.), Mr. G. Blain (Magus Restoration Ltd.) and Mr. T. Nicholas (Golder Associates) for on-site cooperation.

Dr. D. Nixon (PWC) for providing reference material.

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EXECUTIVE SUMMARY

INTRODUCTION

This report presents an overview of the most important aspects of corrosion-induced parking structure deterioration resulting from repeated exposure to roadway deicing salts and moisture. An assessment of repair and maintenance options is provided for multi-story cast-in-place reinforced concrete underground parking garages, which typically require comprehensive repair schemes to correct deficiencies. The document is intended as a reference for technical audiences not yet fully conversant with the deterioration problem and uses data derived from two previous Canadian field studies.

SCOPE

Key issues discussed in this report are:

- causes and examples of deterioration
- factors which influence deterioration rates
- techniques to evaluate the extent of deterioration
- current repair options and practices
- inspection/maintenance procedures
- economic issues.

FINDINGS

Causes of Deterioration and Influencing Factors

The primary cause of reinforced concrete parking structure deterioration is attributed to reinforcement corrosion. The corrosion results from the combined presence in the reinforced concrete of moisture, oxygen and chloride ions originating from road deicing salts. Corrosion deposits at the level of the reinforcement have an increased volume over the uncorroded reinforcement, causing concrete to crack. Cracking promotes increased water penetration into concrete causing additional durability problems such as spalling and scaling, and exacerbates serviceability problems such as staining, leaching and through-slab water penetration.

Although the dominant cause of parking structure deterioration is attributed to corrosion of the steel reinforcement promoted by road salts, other factors such as inadequate drainage slopes, deteriorated drains, electrical conduit embedments and poor maintenance programs all contribute to premature degradation of parking structures.

Investigation Program

To establish the extent and causes of deterioration, a preferred investigation program is presented. This approach

consists of two phases; a visual survey carried out to gain insight into the extent and structural implications of the defects and, a second phase to quantify and detail the damage. Primary field investigation techniques include:

- a delamination survey using the chain drag method
- concrete cover survey using a pachometer
- corrosion assessment using half-cell measurements.

A table is included which summarizes field and laboratory test parameters and applicable reference standards. In cases where an analytic approach to slab strength assessment is difficult or impractical, load testing may be considered. A checklist is included, as Appendix B, which can be used as a guide when making a parking structure condition survey.

Repair Strategies

Various repair options and detailed step-by-step restoration techniques are presented. Although each project must be considered on an individual basis, most repair schemes can use the following approach:

- removal of deteriorated concrete
- cleaning reinforcement and replacement as required
- concrete replacement
- surface treatment.

Various concrete surface treatment schemes are outlined including modified concrete overlays using polymer or epoxy additives and barrier systems using membranes or sealers.

Economic Issues

A life cycle cost technique is provided which can be applied to a broad range of repair cases in order to arrive at cost-effective repair solution. Comparisons are given which show overall costs for a structure repaired using sealer and membrane systems.

CONCLUSIONS

Many variables influence parking structure repair costs. Variables such as garage configuration, structural details, functional details, financing aspects and lack of long-term performance data on barrier systems make it difficult to establish specific cost-of-repair principles. Regular ongoing maintenance programs are found to be cost-effective through reduced damage and minimized lost revenue. Barrier system patching, functioning drains, and washing down of salt contaminated floor surfaces are important factors in the prevention of premature deterioration. Appendix A summarizes important code development and research work aimed at improving parking structure durability.

1.0 INTRODUCTION

1.1 Background

This report is intended as a reference document which presents an overview of the most important aspects of parking structure deterioration. It deals mainly with problems related to corrosion induced deterioration of multi-story cast-in-place reinforced concrete underground parking garages. The corrosion is caused by the electrical interaction of chlorides, oxygen, and water with the steel reinforcement. Such chlorides may penetrate the concrete surface as deposited road salts, or may have been added to the concrete as an admixture. This report is not intended to be exhaustive from a theoretical point of view. The emphasis is directed at basic concepts most important to a technical audience not yet fully conversant with the problem.

The document will begin by examining the basic causes of deterioration of parking structures - why concrete structures which generally can provide corrosion protection are particularly vulnerable to chloride intrusion. This assessment will be followed by a review of methods which have been developed to determine the extent of damage. Together, these sections will serve as the basis for the following chapters dealing with various repair options as well as with ongoing maintenance and inspection procedures. Economic issues will be discussed to provide an introduction to cost-effective aspects of parking structure repair work and maintenance.

This document represents the third study carried out by CMHC concerning parking structure deterioration. The first two studies were carried out by J.A. Bickley of Trow Ltd. and were published in 1981 and 1984 respectively. The 1981 study, published under the name "Nature, Extent and Impact of Residential Parking Structure Deterioration" dealt mainly with an assessment of the economic impact of residential parking structure deterioration. The data for that report was generated through a survey and analysis of problems in 84 parking structures in Ottawa, the majority of which were heated parking garages. The following conclusions were reached from this study:

- in 1981 dollars, approximately 10.75 million dollars would have been required to repair these 84 structures, giving an average cost of about 1200 dollars per parking space

- a financial analysis confirmed even then that in the long run, repairs carried out to high standards would be significantly cheaper than the use of less desirable but initially cheaper repair methods.

The 1984 study, "Parking Structure Deterioration: A Survey and Analysis of its Extent and Influencing Factors" dealt with the technical aspects of parking structure deterioration. This survey attempted to identify factors which favourably affected the serviceability of parking structures. Additionally, it tried to assess cost-effective repair measures by monitoring the performance of various repair schemes. The data was primarily based on heated reinforced concrete parking structures in Toronto, Montreal and Ottawa. The following conclusions were reached:

- durable new parking structures could be built with proper attention to design, construction and maintenance details which reduce the penetration of deicing salts to the reinforcement

- rehabilitation of existing damaged parking structures is possible, however some further deterioration is inevitable unless all active chloride contaminated concrete is removed

- the rate of deterioration after repairs can be substantially less than the rate of deterioration prior to repairs, if replacement work is well done.

The present document will reference key points from the 1984 survey and provide additional material for an overview of parking structure deterioration and repair.

1.2 The Canadian Situation

Major parking structure deterioration first became apparent in the late 1970's and the problem became widespread within about a decade. Specific studies have not been done which considered the effects of regional variations in road salt usage on the rate of parking structure deterioration. Because the primary cause of deterioration has been linked to road salt induced corrosion, higher rates of deterioration would be expected in regions with high road salt usage.

The overall cost of repairs to damaged parking structures in Canada has been estimated at 1.5 to 3.0 billion dollars, and studies have shown that the repair costs for individual structures can exceed the original construction costs.

At the present time, representatives from the construction industry, design profession, and technical committees are addressing joint concerns of deterioration to existing structures. In 1983 a committee was formed to draft CSA Standard S413M, "Durable Parking Structures". This standard, expected to be published in 1986, deals specifically with the design and construction of new durable parking structures.

A chronological history of important publications and code work is given in Appendix A.

1.3 Scope

The document is directed at evaluation of and repairs to heated, cast-in-place, underground parking garages which typically have suspended slabs. The rates of deterioration in these structures are generally higher than in other parking structures due to increased rates of deposition of salts from melted snow, humidity effects, and the cyclic nature of wetting. Additionally, the repair measures can be more difficult and expensive due to limited access, limited hours of work, and increased loss of revenue during the repair time period. In general, the concepts covering causes of deterioration and evaluation techniques apply to other forms of construction. However, each project should be assessed on an individual basis with respect to the extent of structural damage and the most appropriate repair options.

2.0 CAUSES AND TYPES OF DETERIORATION

2.1 Overview of the Problem

Parking structures are subjected to demanding service conditions. These include live load effects such as vehicular impact and abrasion as well as environmental effects such as high humidity and moisture levels, thermal variations, and attack from deicing salts. Together these factors can lead to premature deterioration of parking structures even when constructed to meet appropriate building codes. This section of the report will examine the most important causes and types of parking structure deterioration which generally depend on many interrelated factors covering concrete design, material properties, workmanship and maintenance procedures.

Structural steel reinforcement is protected from corrosion when placed in concrete due to the chemical relationship between steel and concrete. This protection is lost in the presence of chloride in the concrete, primarily introduced into the concrete as dissolved road salts which will migrate through unprotected concrete to the level of the reinforcement. The corrosion process, the results of a time dependent reaction between moisture, oxygen and iron in the reinforcement, causes the formation of corrosion deposits which have an increased volume over the uncorroded reinforcement. Consequently internal stresses are developed which can ultimately rupture the concrete mass. This process can cause concrete delamination, loss of concrete section, debonding of reinforcement, and reduction in reinforcement cross-section, all of which can impair structural integrity.

Also, as the concrete mass becomes increasingly porous from the development of interconnected cracks, the potential for increased rates of corrosion exists. This basic corrosion-delamination mechanism is explained in Fig. 1 and the self-generating nature of the problem is explained in Fig. 2.

Additional types of parking structure deterioration which will be discussed include cracking, leaching, scaling and deterioration at joints. The discussion will be directed towards basic failure concepts and will summarize the key factors which have been identified as influencing deterioration rates. Through an understanding of this background material, further report sections dealing with techniques used in evaluating the extent of deterioration and procedures for remedial measures can be better understood.

2.2 Corrosion-Induced Deterioration

2.2.1 Protection of Reinforcement

Uncontaminated concrete provides reinforcement with significant corrosion protection through two mechanisms. These are passivation of the reinforcement during the cement hydration process and the physical barrier of the concrete cover. The cement hydration process produces calcium hydroxide which induces a pH in the pure solution of approximately 12.5. At this pH level a passive oxide layer quickly forms which prevents direct contact between metal and the solution, hence corrosion does not proceed. Additionally, the concrete can be proportioned to have a low permeability. Low permeable concrete minimizes the penetration of corrosion-inducing substances and increases electrical resistivity which impedes the flow of corrosion producing currents.

2.2.2 Principles of Corrosion

This section will begin by briefly explaining the electrochemical reaction which causes the corrosion of iron in the presence of oxygen and water. Next the additional effect of chloride ions on the electrochemical process will be discussed. Finally, the breakdown of the oxide layer by chloride ions will be treated.

The electrochemical process of corrosion is summarized in Fig. 3. Reinforcing steel is not completely uniform with respect to its chemical or metallurgical structure. Regions of different electrical potential will exist, giving rise to the presence of an anode where corrosion occurs and a cathode. This variation in electrical potential will drive the electrochemical corrosion process. In the presence of moisture, iron at the anode dissolves to form positively charged iron ions, releasing electrons which are conducted

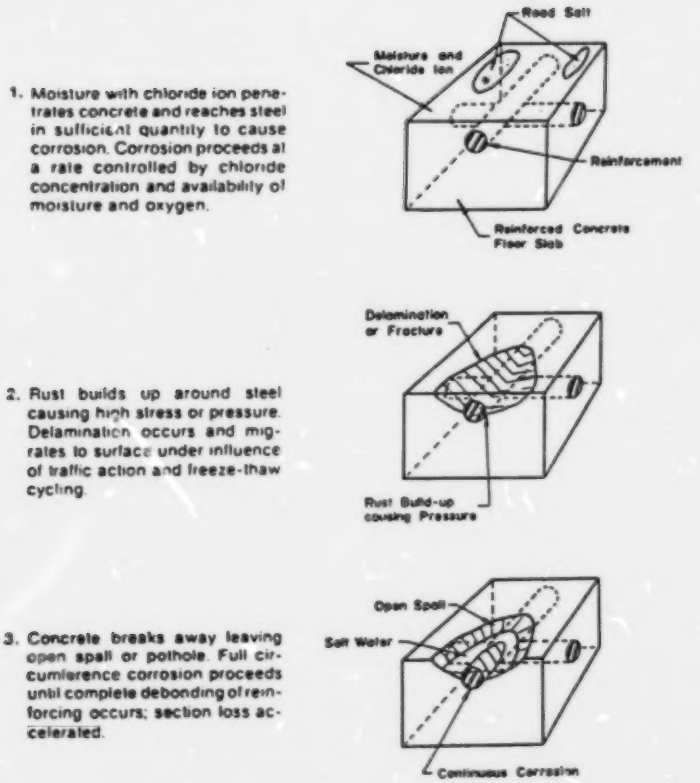

1. Moisture with chloride ion penetrates concrete and reaches steel in sufficient quantity to cause corrosion. Corrosion proceeds at a rate controlled by chloride concentration and availability of moisture and oxygen.
Road Salt
Moisture and Chloride Ion
Reinforcement
Reinforced Concrete Floor Slab
2. Rust builds up around steel causing high stress or pressure. Delamination occurs and migrates to surface under influence of traffic action and freeze-thaw cycling.
Delamination or Fracture
Rust Build-up causing Pressure
3. Concrete breaks away leaving open spall or pothole. Full circumference corrosion proceeds until complete debonding of reinforcing occurs; section loss accelerated.
Open Spall
Salt Water
Continuous Corrosion

Fig. 1 Corrosion - delamination mechanism [1]

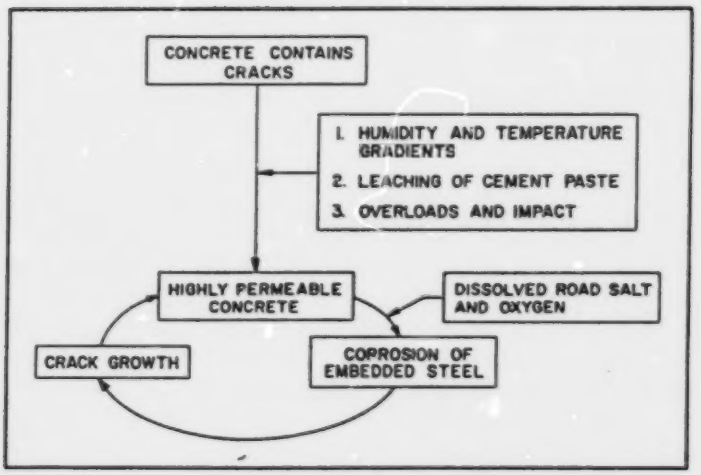


Fig 2 Schematic model of cracking-corrosion interaction. (Adapted from ref. 2)

through the steel to the cathodic sites. At the cathode, the electrons combine with oxygen and water to form negatively charged hydroxyl ions. The negative hydroxyl ions in turn react with the positive iron ions in the solution to form a precipitate which further reacts with oxygen giving ferric hydroxide or red rust. The essential factors required for corrosion are:

- the existence of anodes and cathodes at different electrical potential
- an electrolyte to conduct electrical current
- oxygen.

The presence of chloride ions in the solution greatly increases the corrosion process by increasing the variation in electrical potential over the metal surface and by reducing the resistivity of water.

Two actions have been identified which act to break down the chemically induced corrosion protection of concrete: carbonation and the direct breakdown of the oxide film layer. Carbonation takes place when CO_2 in the air reacts with hydroxides in the pore solution to form carbonates plus water, thereby reducing the pH to approximately 8.3. At this lower pH level, steel will corrode even without chloride ion contamination. Generally, however, corrosion problems due to carbonation are not as significant as those due to chloride ions. In the second process, called depassivation, the oxide layer is attacked directly by chloride ions. The phenomenon is not completely understood. Currently, three theories have been advanced which attempt to explain the mechanism. These are oxide film theory, the adsorption theory and the transitory complex theory[3].

2.2.3 Factors Influencing Rate of Corrosion

Chloride Concentration

Generally, higher chloride levels have been found to cause higher rates of corrosion. However, no absolute consensus has been reached on the minimum chloride concentration level which initiates corrosion. Concentrations are typically specified in terms of % mass of chloride ions per mass of cement or per mass of concrete. A knowledge of the cement content of a particular mixture is required to convert values between the two methods. The issue is complicated by differences in corrosion rates of calcium and sodium chlorides, both of which are used as deicing salts and by differences in rates of corrosion of chlorides mixed with concrete vs chlorides which diffuse into hardened concrete. A minimum value of approximately 0.15 % chloride ion content by mass of cement is thought to be the minimum concentration

required to initiate corrosion. ACI currently specifies permissible chloride ion contents ranging from 0.06 % to 0.15 % by mass of cement for structures exposed to a chloride environment. CSA presently allows up to 2 % by mass of calcium chloride for some types of structures. The results of the 1984 government survey found mean chloride ion levels of 0.16 % by mass of concrete at the level of top reinforcement which was considered to be about twice the level found in bridge decks in North America. A detailed discussion of effects of chloride ion level on corrosion rates is given in Ref. 3, published by ACI committee 222 in 1985.

Moisture Content

Concrete moisture content affects the corrosion rate by influencing electrical volume resistivity. Fully water saturated concrete has an electrical resistivity of about $7x10^3$ ohm cm. This is increased to $6000x10^3$ ohm cm for air dried concrete. Field measurements indicate that above a level of 50 to $70x10^3$ ohm cm steel corrosion is negligible. This demonstrates that corrosion stops early on in the drying process and should not start again unless the concrete becomes almost saturated.

Concrete Mix Factors

Concrete mix factors which promote reduced concrete permeability will decrease corrosion rates by limiting the ingress of water, oxygen and chlorides. Studies have indicated that the water cement ratio is an important mix design factor in controlling corrosion by affecting permeability. The effect of variation in water cement ratio on concrete permeability is illustrated in Fig. 4. Fig. 5 shows the corrosion response of 300x300x150 mm test specimens containing embedded steel at depths ranging from 13 to 50 mm for various water cement ratios. The onset of corrosion activity is indicated by the sharp jump in the curve of potential vs time. The beneficial effect of reducing water cement ratios, for instance from 0.60 to 0.45, is particularly effective when concrete cover is increased.

The influence of variations in cement content are less clear. Tests which vary cement content, keeping water cement ratios constant, have found little significant variation in protection of reinforcement. Higher cement contents, however, will allow lower water cement ratios and still maintain workability. Little work has been directed at examining the effect of aggregate size, shape or gradation on corrosion rates.

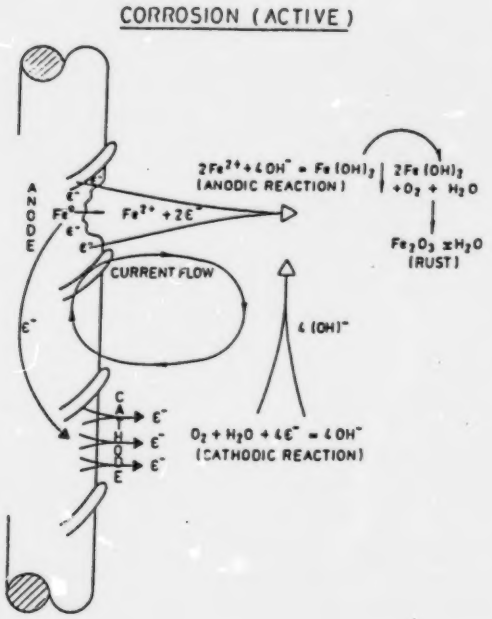


Fig. 3 Electro-chemical corrosion mechanism[4]

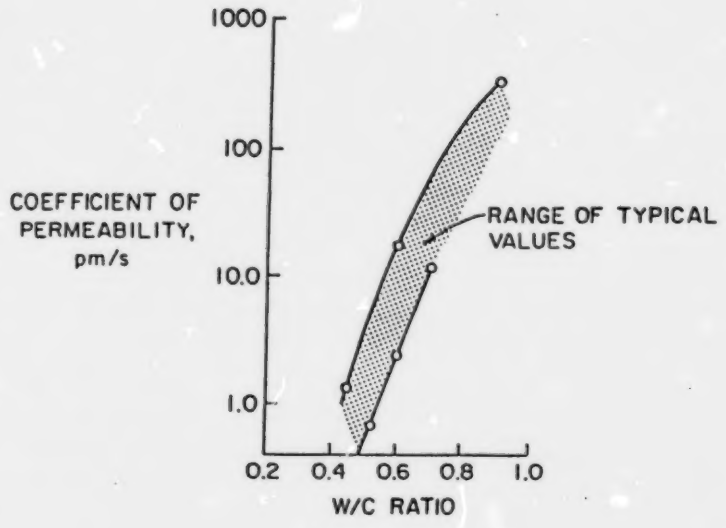
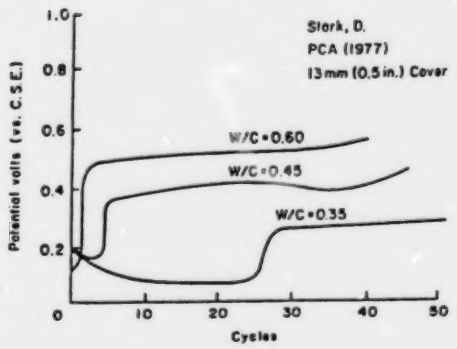
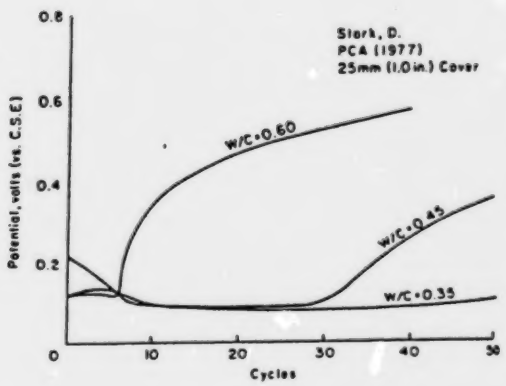
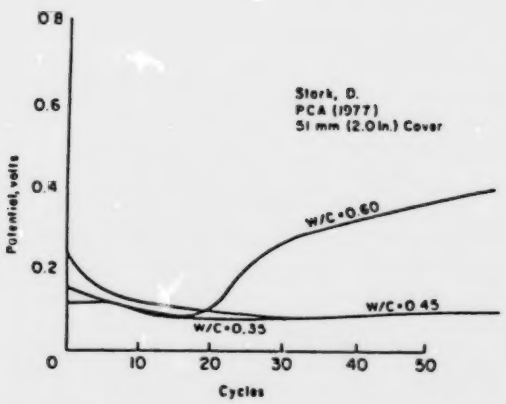


Fig. 4 Permeability[5] of concretes as influenced by w/c ratio







Notes:

- tests were conducted on 300 x 300 x 150mm samples
- each cycle consisted of 4 days ponding with a 3.5% NaCl solution followed by 10 days drying at 50% relative humidity
- active corrosion is indicated by a sharp jump in the potential vs cycles curve.

Fig. 5 Effect of variations in w/c ratio on corrosion activity for concrete cover ranging from 13 to 51mm.[6]

Thickness of Concrete Cover

Increasing concrete cover has been found to significantly reduce the corrosion rate of reinforcement primarily by reducing penetration of chloride ions. The relationship between chloride ion penetration and concrete cover is illustrated in Fig. 6. The relationship is typically non-linear because the diffusion of chloride ions is influenced by both concrete permeability and chemical binding effects. In the past, codes allowed a concrete cover of as little as 20 mm for parking structures. Current CSA code practice does not specifically state cover requirements for reinforcement in corrosive environments. The 1984 government survey of 36 structures found an average concrete cover of 42 mm which would seem to indicate adequate concrete cover. However, the survey also found significant variations in concrete cover, ranging from approximately 0 to 115 mm. Also, a comparison was made to a 1976 Ontario Ministry of Transportation and Communications survey which looked at the relative compliance of reinforcement cover with specifications in bridge decks. Although consideration should be given to the simpler placement of reinforcement in bridge decks, compared to that of parking structures, the 1984 government survey found that 81 % of the structures surveyed had cover variations which exceeded those considered typical of a diligent bridge contractor. This variation in reinforcement placement has implications which should be considered by designers when specifying minimum cover requirements for parking structures.

2.2.4 Corrosion-Induced Deterioration

Degradation of both the concrete mass and steel reinforcement results in deterioration of parking structures due to the direct effects of reinforcement corrosion. Concrete deterioration initiates with expansive stresses induced by the build-up of corrosion products. These products are associated with an increase in volume ranging from about 3 to 6 times the uncorroded volume of the affected metal. When the tensile capacity of the concrete is exceeded, horizontal separations, called delaminations, are induced. As the corrosion process continues, these horizontal fractures can reach the concrete surface which can eventually break into dish shaped cavities called spalls. The process is further aggravated by traffic action. In addition to concrete degradation, significant loss of reinforcement cross section and debonding between reinforcement and concrete can occur. All these effects can have significant structural implications. Areas which have a concentration of top reinforcement, such as column capitals and one-way floor slabs over beams, can be especially vulnerable. Particularly dangerous situations can arise when corrosion deterioration simultaneously reduces the concrete

section designed to act in compression/shear and the tensile capacity of the reinforcement.

The 1984 survey found measurable delamination growth to begin typically after approximately five years of service. The rate of increase was found to be highly variable over the region of deck area monitored and thought to be controlled by local factors such as the amount of top reinforcement, concrete quality, cover thickness, variations in temperature, and chloride deposition rates. Fig. 7 summarizes the results of time effects on delamination growth for various types of structures when repairs were not made.

2.3 Cracking

Although corrosion can occur in concrete without significant visual cracking, the corrosion-cracking interaction issue has not been fully resolved. It is clear that concrete will contain cracks prior to the onset of corrosion, and that these cracks when interconnected will promote corrosion. Also, because of the expansive products formed during corrosion, cracking is a result of corrosion. Arguments have been advanced that because chloride penetration to the reinforcement occurs so quickly, effects due to cracking are minimal. Additionally, little correlation has been found between design crack widths and corrosion rates.

Cracking can have structural, visual and serviceability implications. Questions regarding structural implications of cracking should consider the movement of cracks as well as the extent and frequency of cracking in relationship to the location of reinforcement. Serviceability effects of cracking result from the increase in transmission of chlorides and cement paste products and will be discussed under deterioration due to leaching. A number of criteria have been developed by ACI, OMTC, and CMHC which can be used to clarify extent of cracking[7].

2.4 Leaching

As water migrates through a concrete slab, the lime component of the cement paste can be dissolved and combined with previously dissolved chlorides, eventually resulting in the build up of stains and films on the slab underside. This deterioration process called leaching can lead to both serviceability and structural deficiencies. In addition to surface staining, leaching can cause finish damage to vehicles from the highly alkaline solution. Mechanical and electrical services embedded in concrete slabs or suspended from below can also be affected either by corrosion or the buildup of dissolved deposits. Leaching over a period of time can reduce concrete strength by breaking down the aggregate/paste and reinforcement /paste bond. The resulting

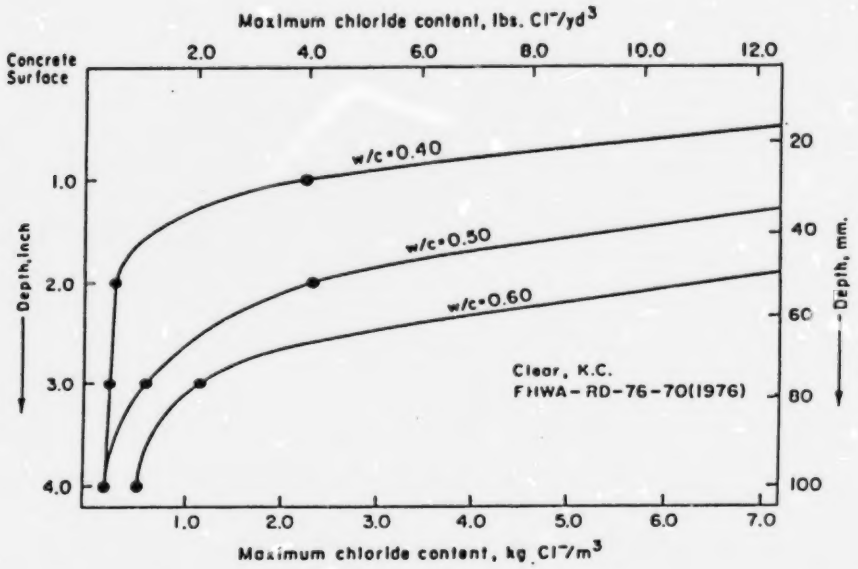


Fig. 6 Effect of depth of concrete cover on chloride penetration after 830 daily salt applications[8]

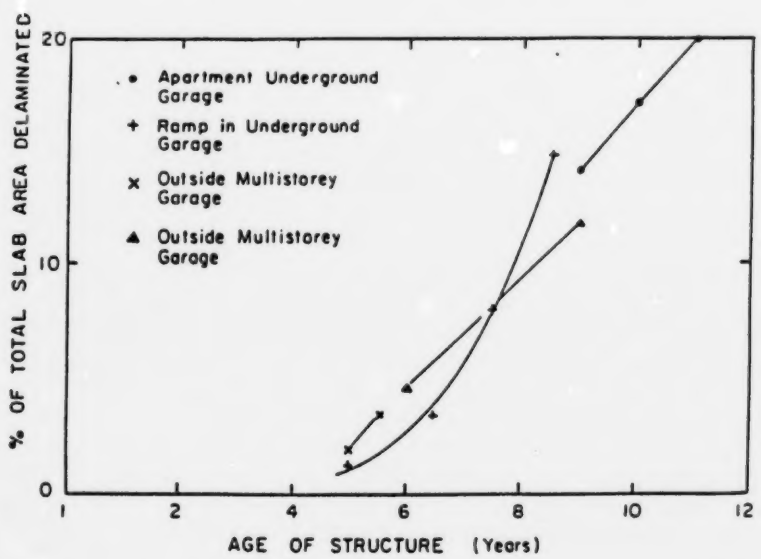


Fig. 7 Delamination growth as a function of time[9]

voids will also increase concrete permeability and hence increase corrosion. Leaching can be controlled by measures which remove surface water and decrease permeability such as properly sloped slab surfaces, freer running drains, barrier systems and correctly designed and maintained joints.

2.5 Scaling

Concrete scaling is a degradation of the concrete surface brought about by freeze thaw action which is aggravated by the presence of deicing chemicals. During construction, scaling can be controlled with proper attention to finishing procedures which do not bleed excessive amounts of water from the concrete surface and by the addition of air entrainment. Initially, scaling begins with minor surface flaking as the mortar fraction of the concrete mix is attacked. Eventually concrete deterioration will penetrate deeper, exposing aggregate and additional mortar. Most cases of scaling are superficial in nature, however the degradation will cause increased concrete porosity and reduce cover. The 1984 survey found that generally for indoor structures, scaling was minor and hence no quantitative assessment of it was made.

2.6 Other Components

Typically joints are introduced into concrete structures to achieve crack control and release restraint effects due to shrinkage and temperature variation. Joint failures are commonly associated with sealant failure due to either impact loading from vehicles, underestimating design joint movements, or failure of concrete adjacent to the sealant. Where joint deterioration has taken place, salt laden water often accumulates. This can lead to local regions of concrete spalling and eventually complete breakdown in the functioning of movement joints.

Surface water build-up can cause concrete deterioration through leaching, staining and the infusion of additional chlorides from standing salt-contaminated water. Drainage paths must be provided by sloping slab surfaces to free running drains. Drains must be installed at slab low points and designed so that they are easily accessible for cleaning and are positively sealed to the adjacent concrete slab.

3.0 EVALUATING EXTENT OF DETERIORATION

3.1 General Approach to the Investigation

The objectives of an investigation program into parking structure deterioration are firstly to establish the nature and extent of deterioration, secondly to determine the underlying causes of the deterioration and thirdly to

develop a comprehensive repair scheme. The repair scheme should address itself to both the correction of existing problems and protecting against potential future deterioration in a cost-effective manner for the remaining service life of the building.

The nature of parking structure deterioration varies widely. Some kinds of deterioration, such as cracking and spalling, are readily apparent from a visual survey, while other potentially more serious problems such as reinforcement corrosion require special techniques to establish. Table 1 summarizes the specific applications and limitations of investigative techniques, together with the governing standards. Details are discussed in the following sections.

The investigation procedure itself must be systematic and thorough in order to be representative. The following two-phase approach to the investigation can be used as a general guide in order to carry out the investigation. It presents a comprehensive approach to the investigation which, however, would not always be warranted on all projects. Because the project size and extent of deterioration varies, details regarding the number and type of tests must be assessed on an individual project basis. Two useful documents, which will provide additional details and background information into parking structure investigations, are: "Interim Guidelines, Investigation, Repairs, Design and Construction of Parking Structures" published by the Ontario chapter of ACI and "Guide For Making a Condition Survey of Concrete in Service" authored by ACI Committee 201. Additionally, a checklist for a parking structure condition survey is included as Appendix B. It is a simplified version of more detailed forms which were used in the 1984 survey; the checklist of Appendix B could serve as a guide for either a Phase I or Phase II Investigation depending on the size, complexity and amount of damage in a parking structure.

3.2 Phase I Investigation - Preliminary

The Phase I Investigation is primarily a visual survey done in order to establish the nature of the problem, plan the detailed investigation and gain insight into the structural implications of the defects. The following points should be covered in a Phase I Investigation:

- A document review in order to establish design details and construction history. This would normally include review of the as-built architectural/structural drawings, specifications, construction documents and records of previous repairs. Particular attention should be given to reinforcement details regarding size, typical spacing and specified cover requirements.

Table 1 Summary of Phase II Investigation Tests

Test Name	Parameters Measured	Test Limitations	Reference Standards
Chain-Drag Survey	horizontal concrete delaminations	accurate to a depth of approximately 150 mm	
Covermeter Survey	thickness of concrete cover	accuracy of ± 3mm up to 40 mm and ± 5mm for cover > 40 mm	BS 4408: Part 1: 1969, Recommendations for Non-Destructive Methods of Test for Concrete, Part 1: Electro-Magnetic Cover Measuring Devices
Half-Cell Tèsts	corrosion activity	measured potentials related to statistical probability of corrosion	ASTM C876-80, Half-Cell Potentials of Reinforcing Steel in Concrete
Chloride Penetration	rate of chloride ion penetration Test no. 1 "Slow test"	slow test takes approximately 90 days	AASHTO T 259-80
	Test no. 2 "Quick test"	quick test takes 6 hours	Portland Cement Association for the Federal Highway Administration
Chloride Content	Cl^- levels in concrete	allowance must be made for Cl^- levels for aggregates and admixtures	FHWA-RD-77-85 Sampling and Testing for Chloride Ion in Concrete
Concrete Quality	compressive strength, cement content, density, air content		CAN3 A23.1-M77 CAN3 A23.2-M77
Electrical Resistance	membrane permeability		Durability of Concrete Bridge Decks, NCHRP Synthesis no. 57, Transportation Research Board, Washington D.C., 1979, 60pp.

- A visual inspection and photographic record of the entire structure,including attention to the structural frame, joint details and drainage systems. Details can be noted on a site plan. Records should be made of visual defects such as delaminations, spalls, staining, scaling and cracking. Crack widths should be noted and attention given to location of underlying reinforcement crossing cracks. Drainage systems should be investigated, to check for blockage and effectiveness of slopes.

- Sample removal of pieces of spalled concrete can allow preliminary examination of the extent of reinforcement corrosion. Additionally, small concrete samples, at various depths, can be drilled and collected for laboratory chloride content tests.

- Chain drag surveys and covermeter tests which measure delaminations and concrete cover respectively, can be carried out at a number of locations. Such locations should be typical of structural details, use-patterns and extent of visual deterioration found in a particular structure.

3.3 Phase II Investigation - Detailed

Once the Phase I Investigation is complete and it is determined that further work is justified, a Phase II Investigation should be undertaken in order to determine quantitatively the following key items:

- extent of corrosion
- extent of delamination
- concrete cover
- chloride level
- concrete permeability
- concrete strength.

The amount of area which is surveyed in detail will vary from about 20 % to 100 % of the surface area. Grid systems can be established, using chalk lines or lumber crayons on the concrete slab surface in order to transfer field survey data to site plans. Grid systems typically range in size from about 1x1 m to 2x2 m and are normally oriented along column lines.

3.3.1 Delamination Survey

Regions of horizontal concrete separations are surveyed using the chain drag method. This simple technique involves passing a chain over the concrete surface in a swinging motion in direct contact with the concrete. Various lengths of chain are used, ranging from a single piece approximately 1.5 m in length to the use of four shorter chains approximately 0.5 m long attached to a wooden handle. As the device is swept from side to side in a swinging motion, dull sounds from within the slab indicate areas of delamination, while higher pitched ringing sounds indicate regions of sound concrete. Once the general area of delamination is determined, a hammer is used to establish the extent of delaminations in greater detail by tapping the concrete surface. The delamination boundary is recorded on the concrete surface using spray paint.

3.3.2 Concrete Cover

Concrete cover depth is determined using a pachometer, also referred to as a covermeter. The device is a battery-operated electromagnetic instrument which indicates distortions in an applied magnetic field caused by the presence of steel reinforcement. Once the reinforcement bar size is known, the instrument can be calibrated to indicate thickness of concrete cover. Two types of pachometers are commonly used, a hand-held device and an automated device mounted on wheels. The accuracy of the instrument is approximately ± 3 mm up to 38 mm and ± 6 mm over 38 mm of concrete cover. The accuracy can be verified by visual examination of bars exposed in delaminated areas or by coring.

3.3.3 Extent of Corrosion - Half-Cell Measurements

This test is used to indicate, in a non-destructive way, the activity of reinforcement corrosion. While it will not give specific corrosion rates, it will indicate if the reinforcing steel is in an active or passive state. The device is based on the fact that active corrosion will cause a voltage differential to develop between the reinforcing steel and the copper-copper/sulphate electrode. The device consists of a ground lead connected to exposed steel reinforcement, a voltmeter and a copper-copper/sulphate half cell. A porous stone in contact with the cell and wet sponge in contact with the concrete surface complete the circuit. The instrument is placed in contact with the concrete surface at gridline intersections and voltage readings are taken. The concrete surface sometimes must be pre-wetted in order to allow current to flow. The following range of corrosion activity has been referenced to the copper-copper/sulphate

half cell:

- potentials numerically less than -0.20 V indicate a greater than 90 % probability of no active corrosion
- potentials in the range of -0.20 V to -0.35 V indicate corrosion activity is uncertain
- potentials numerically greater than -0.35 V indicate a greater than 90 % probability of active corrosion.

By plotting the half-cell voltage readings on a site plan grid, equipotential contour maps can be developed to graphically display regions of corrosion activity.

3.3.4 Concrete Permeability

Two tests have been developed to measure the rate of chloride ion penetration into concrete. A "slow" test consists of applying a 3 % sodium chloride solution to the surface of a concrete slab. Over a period of 90 days, samples are taken at various depths to measure chloride content. Recently a rapid test procedure has been introduced by the Portland Cement Association. It uses 100 mm cores, 50 mm long. An important advantage of this test is that the permeability of sealers, overlays and waterproofing treatments can be tested. The technique consists of monitoring the amount of electrical charge which has passed through a specimen subjected to a constant electrical potential. The sample is immersed on one side in a sodium chloride solution, hence chloride ions are forced to migrate through the concrete, due to impressed electrical potential. The lower the total electrical charge which passes through the sample, the more impermeable the concrete is to chloride ions. A schematic of the mechanism is shown in Fig. 8. Table 2 gives typical readings for 'concrete alone' and for 'surface treated concrete'.

3.3.5 Chloride Levels

Chloride ion content levels are laboratory tested using an acid extraction process. Samples can be provided using either samples cut from cores or powder obtained by drilling into the concrete. The results are expressed as a ratio between mass of chloride ions and cement content. When the repair budget is limited and the deterioration is fairly extensive, this test may have limited application; for such conditions it will simply confirm that overall chloride ion levels are substantially greater than the threshold level.

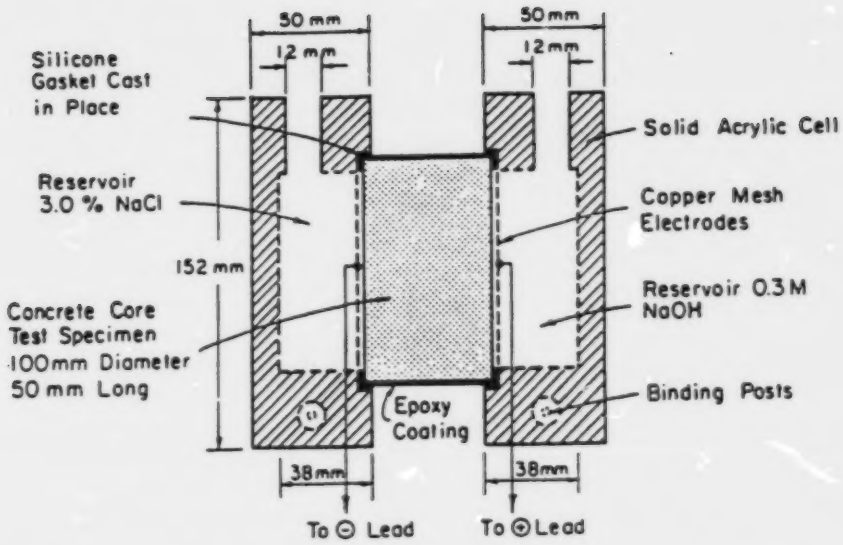


Fig. 8 Schematic of the PCA permeability test apparatus[10]

Table 2 Range of PCA Concrete Permeability Test Results[11]

Interpretation of Results		
Chloride Permeability	Charge Passed (coulombs)	Type of Concrete
High	4,000	High water-cement ratios (0.6)
Moderate	2,000 to 4,000	Moderate water-cement ratio (0.4 to 0.5)
Low	1,000 to 2,000	Low water-cement ratios "Iowa" dense concrete
Very Low	100 to 1,000	Latex modified concrete Internally sealed concrete
Negligible	100	Polymer impregnated concrete Polymer concrete

3.3.6 Concrete Quality

The following standard tests can be used to obtain an overall impression of concrete quality. Test details are given in CSA CAN3-A23.1-M77 and CAN3-A23.2-M77.

- compressive strength tests
- cement content
- density
- air content.

3.3.7 Electrical Resistance Measuring Equipment

Electrical resistance measurements are performed on waterproofing membranes made of dielectric materials. Relationships have been established between resistance, the number of holes in a membrane and its permeability to water. Resistance is measured using a copper contact plate which is placed on the membrane surface, an ohmmeter and a ground lead connected to reinforcing steel. Test limitations are discussed in the reference given in Table 1.

3.3.8 Slab Slopes and Drains

Slab drainage paths can be determined by recording regions with standing water and by using surveying instruments to measure elevation changes. This will give an indication of areas susceptible to ponding. The accurate location and condition of drains must be established to indicate overall drainage problems, and where new drains should be added.

3.3.9 Data Presentation

Presentation of data can be handled in a number of ways. Visual information recording spalling, leaching and cracking can be transferred to site plans. This typically gives views of the slab surface, however significant damage is also sometimes recorded on the underside of slabs. A useful pictorial technique is to use colour coded transparent overlays for the various test measurements. By superimposing the transparencies, correlation between slab low points, areas of delamination, and corrosion activity can be readily seen. Figs 9 to 11, taken from the field records made for the 1984 survey, show examples of data presentation from visual, delamination and electrical potential measurements. Increasingly, computer generated graphics are used. These techniques decrease data preparation time and allow for a more flexible use of data.

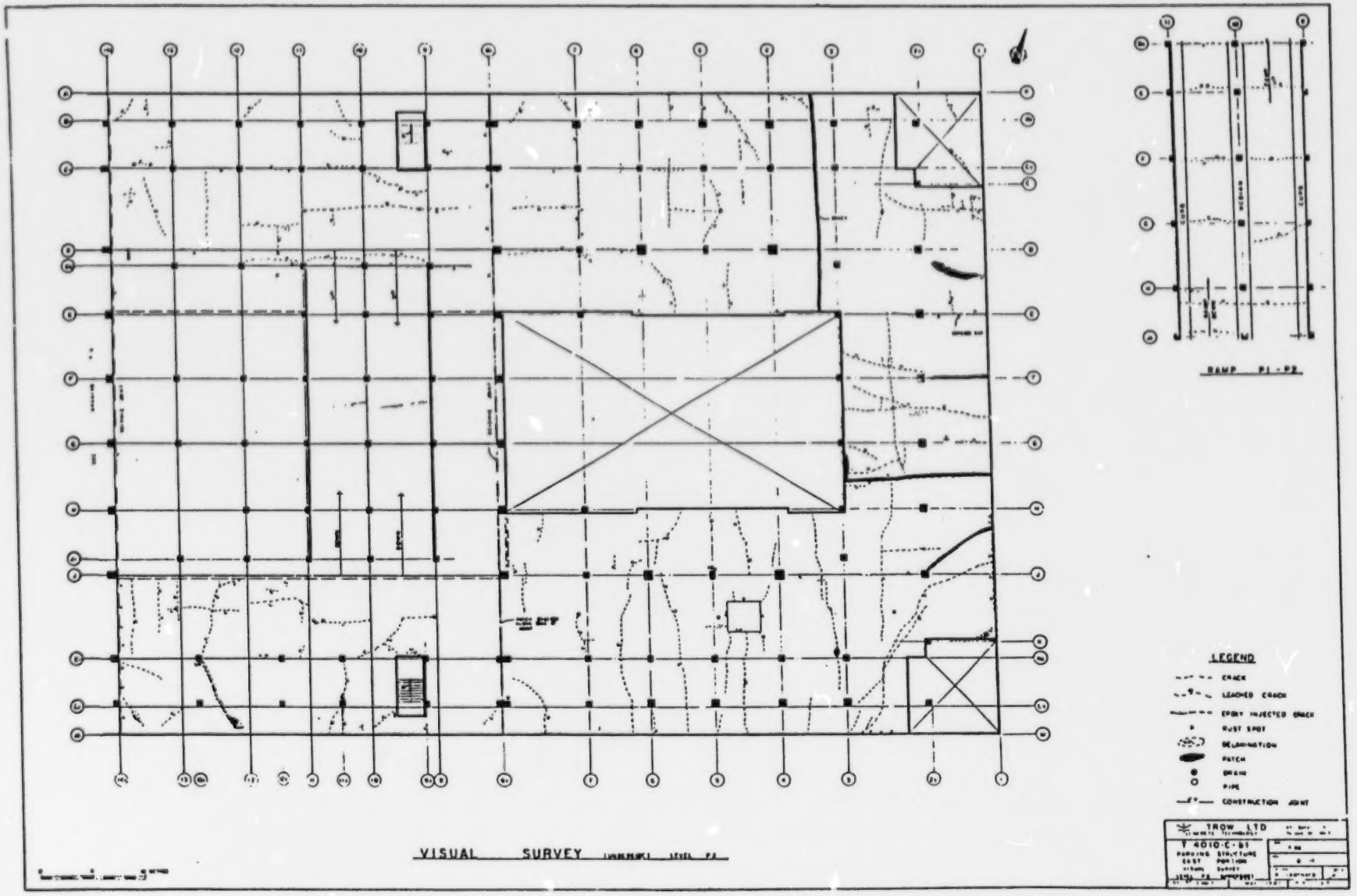


Fig. 9 Results of a visual survey showing extent of cracking

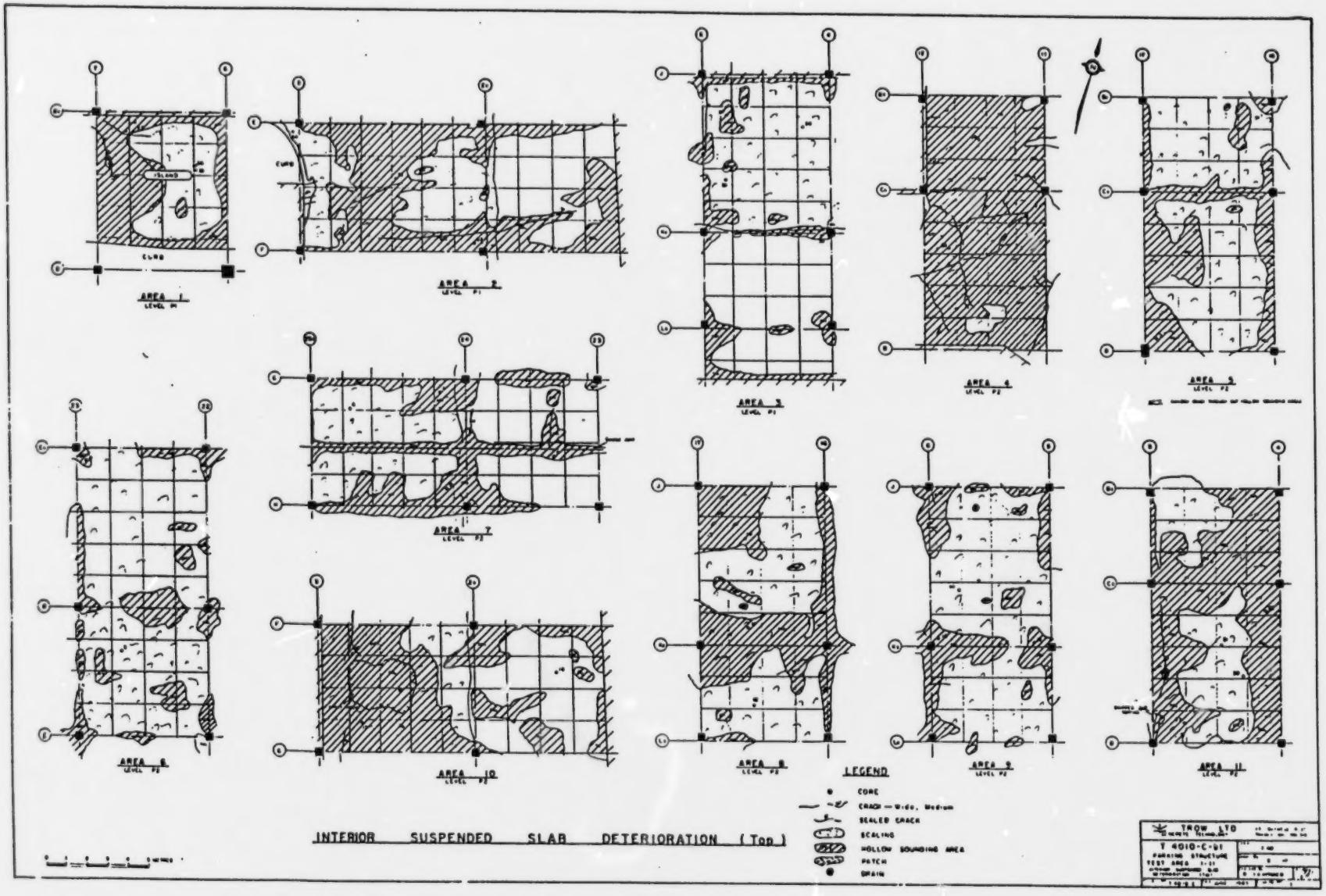


Fig. 10 Results of a chain-drag survey
Delaminated areas are identified by the DEL designation

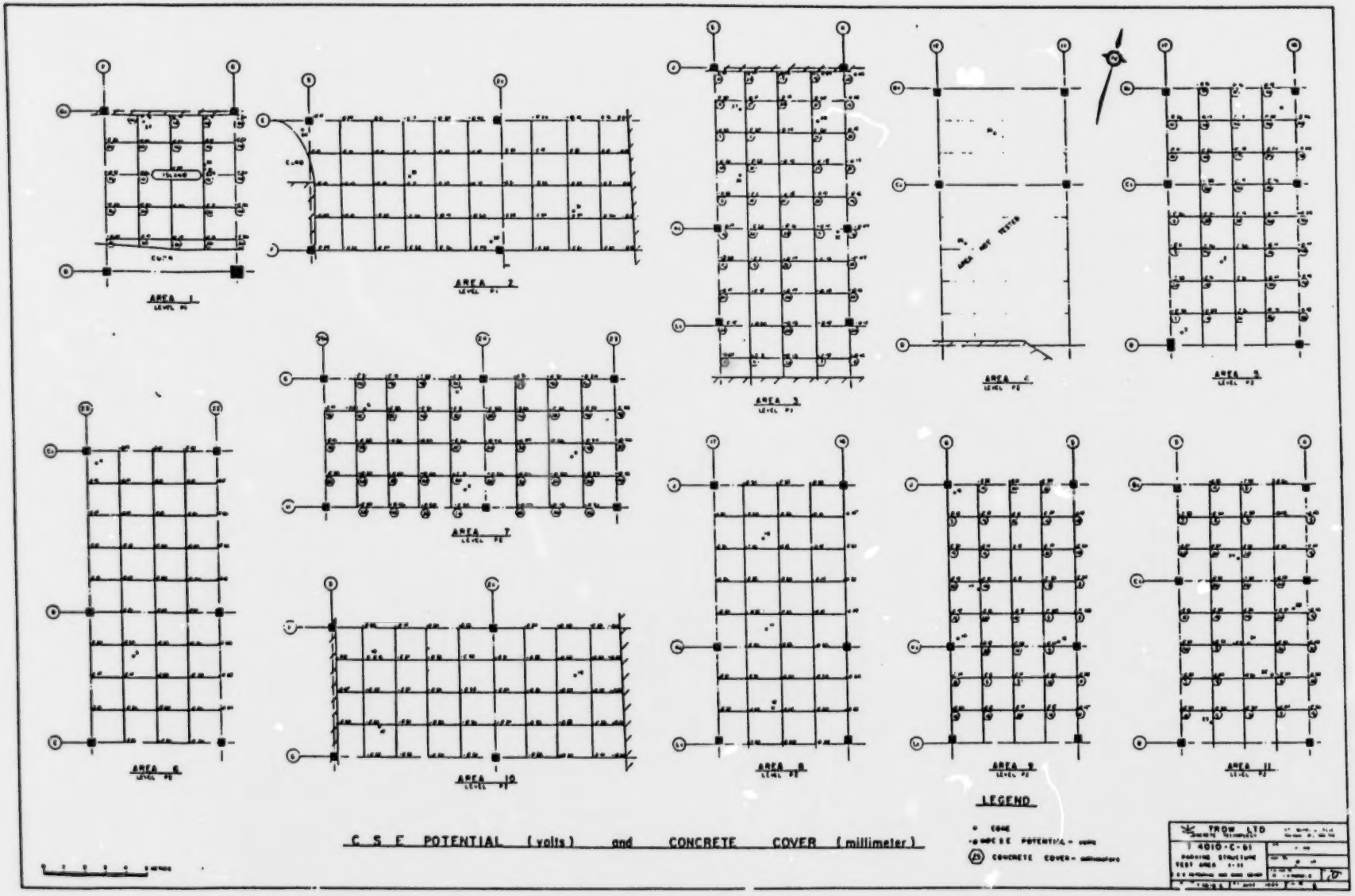


Fig. 11 Results of a Half-Cell survey to determine corrosion activity

4.0 REPAIR OPTIONS AND TECHNIQUES

4.1 Repair Strategy

The repair strategy must address itself to structural, economic and functional considerations. Economic issues will be discussed in Section 6. Although there are many approaches to correction of corrosion induced deterioration of concrete, the basic objectives are to restore structural integrity and delay the onset of potential future deterioration in a manner that is judged to be cost-effective for the life of the building. The first step in the development of a repair strategy will be to assess the results of the condition survey. Causes can often be attributed to a combination of high chloride levels, low concrete cover and relatively permeable concrete. Since in most cases it is not possible to alter the corrosion-inducing environment, the repair method must be directed at means of isolating the reinforcement from chloride contamination. Isolation of the reinforcement is most often achieved by application of a physical barrier system. Recently, cathodic protection systems which electrically isolate chlorides from reinforcement have come into use on parking structures.

This section will begin with a summary of general structural and functional considerations which various repair schemes should address. Next, a summary of practical repair options will be given and details of reinforced concrete restoration will be outlined. This will be followed by a review of important aspects of the various barrier systems and by sources of detailed information. A separate section will explain the principles of cathodic protection. The section will conclude with a summary of survey data from the 1984 survey which examined the performance of various barrier systems.

4.2 Structural Considerations in a Repair Program

The structural consequences of deterioration have been explained in previous sections. Information from the chain-drag survey will give an indication of the extent of damage. Using this information, together with the results of the visual survey and material property strength results, a structural analysis should be carried out. This will establish:

- the present safety of the structure. In some cases it may be necessary to partially or completely limit traffic
- the capacity of the structure to sustain additional dead load which would be required for a concrete overlay barrier system

- the extent to which damaged concrete can be removed in a particular area and shoring requirements. The placement of shores will vary with the extent of damage and sequencing of the repair work. Loads during repairs must be transferred by shoring floor to floor to the level of the foundation. In some cases shoring may be required in damaged parking structures in which repair measures are delayed.

Compatibility of original and repair material properties must also be considered. This would include attention to differential creep and shrinkage, bond strength and elastic modulus of the host and repair materials. The distribution of load sharing between the original and repaired concrete will be affected by all these properties. In many cases, the contribution of the deteriorated concrete comprising the cover material can be neglected and a reduction in reinforcement cross-section up to about 10 % would be acceptable.

For situations in which an analytical approach to assessment of reduced structural capacity is difficult or impractical a load test may be undertaken. Additionally, a load test can be used to confirm the results of analysis. Strength evaluation load test procedures for concrete structures are outlined in section 20 of CAN3-A23.3-M84. The test procedures specify the magnitude, duration and deflection recovery limits for various structural actions. Loads can be applied in a number of ways including concrete block, sandbags or the use of water retention systems. Limiting aspects of load tests should be carefully considered in any evaluation procedure. Load tests will give information on only a portion of a structure and only at the particular time of the test. In extending the results of a load test to other regions of a structure, one must carefully consider the nature and extent of the deterioration at both the test and untested regions. Certain types of loads, such as lateral loads or those due to restrained volume change, may be difficult to simulate. It may be necessary to use fairly sophisticated loading devices such as hydraulic jacks or modification of the vertical loading system to simulate their effects.

4.3 Functional Considerations in a Repair Program

An assessment should be made of possible restrictions on repair work due to noise, dust, vibration and the use of hazardous materials. Consideration should also be given to modifications to the environment of the structure such as temperature controls and improvements to ventilation. The visual impact of repair measures should be addressed. The length and sequencing of repairs will also have cost

implications arising from loss of revenue and displacement of usable parking spaces.

4.4 Repair Options

The final selection of a repair option will depend on an assessment of the previously discussed factors. Budget limitations, however, may require a phasing of repair work to be carried out over a period of time. Life cycle costing techniques which will be discussed in Section 6 of this report can be used to evaluate various repair options. The following five repair options summarize general approaches to restoration:

1. Epoxy injection of cracks and installation of a waterproof membrane wearing course. Epoxy injection of cracks is effective only if the cracking has stabilized. Further movement after injection will cause a crack to open adjacent to the epoxy, rendering the repair ineffective.

2. Replacement of deteriorated concrete and reinforcement, and installation of a waterproof membrane and wearing course.

3. Replacement of deteriorated concrete and reinforcement, and installation of a dense concrete overlay.

4. Replacement of deteriorated concrete and reinforcement, and installation of a cathodic protection system.

5. Complete demolition and rebuilding of structure.

Additionally, repair measures should be directed at expansion joints and upgrading the drainage system. The various repair approaches have advantages and disadvantages which must be considered on an individual basis. Many structures cannot accommodate additional dead loads or reduced clearances which a concrete overlay would impose. For this situation, either additional concrete removal or the use of a thin membrane system are alternatives.

4.5 Restoration Techniques

4.5.1 Concrete Removal

The extent of concrete removal will generally be determined by the delamination survey; ideally all concrete containing chlorides in excess of the threshold value for corrosion should be removed, however, this may not always be practical. The perimeter surrounding the region to be

removed should be saw-cut to a depth of at least 15 mm. The concrete should be removed to sound concrete and to sound uncorroded reinforcement. This can be done using light jack hammers which must be used in a manner which minimizes damage to underlying or adjacent sound concrete. Recently, high pressure water blasting techniques have also come into use. Such a technique has the advantage of reducing damage to underlying concrete caused by jackhammer impact and of possibly achieving higher bond strengths between original and repaired concrete.

4.5.2 Reinforcement Preparation

Reinforcement must be sandblast cleaned to base metal. An assessment must be made of the relative reduction in cross-section due to corrosion. Placement of additional steel is frequently required and this should normally not be welded to existing steel. Lapping of steel or grouted dowels should be used to achieve required development. New steel is normally epoxy coated. Original steel should be hand painted with an epoxy paint. Some disagreement exists over the need to apply epoxy coating to existing steel. Some professionals believe that since the majority of reinforcement is left untreated and the application of a membrane system will reduce future chloride penetration, epoxy painting reinforcement is not necessary. Other professionals believe that because replacement steel is embedded in uncontaminated concrete, the adjacent uncontaminated concrete will tend to set up large galvanic potentials which can cause accelerated corrosion, hence epoxy painting these areas is necessary. The final decision can be guided by the overall extent of damage, budget limits, and experience and confidence in the barrier system.

4.5.3 Replacement of Concrete

A bonding agent should be applied prior to placing concrete to ensure effective adhesion between original and replacement concrete. Three general types of bonding agents used in concrete patch repairs include sand-cement grout, epoxy resins and polymer additives. Field experience has demonstrated advantages and disadvantages with each material and selection of a particular agent depends on consideration of economics, past field experience, construction practice and service conditions. Sand-cement grouts, containing a mixture similar to the mortar function of the concrete patch material, have a proven record of successful field use particularly on bridge deck overlays for over 15 years. Epoxy resins offer increased strength, water resistance and resistance to chemical action together with shortened curing times of approximately 6 hours. However, failures in the epoxy-parent material bond can take place because of differences in the coefficient of thermal expansion between the two materials. Polymer additives have decreased

moisture penetration characteristics and shortened curing periods. The polyvinyl acetate additives have shown to be susceptible to breakdown in repeated exposure to moisture or high PH environments. The concrete mix design should follow the requirements of CAN3-A23.1-M77 and CAN3-A23.2-M77 for Class A exposure with normal density concrete. Typically this will require an air-entrained mix with a maximum water/cement ratio of 0.45 and a minimum cement content of 360 kg/m^3. Plasticizers may be necessary to provide the required workability.

4.5.4 Surface Treatment

The primary function of surface treatment measures for concrete repair work is to provide a barrier which substantially reduces the penetration of chloride ions and moisture. Additionally the repaired surface must resist wear due to traffic loading. There are two basic approaches to the installation of a protective barrier - the installation of a concrete overlay typically up to approximately 50 mm thick or the installation of a waterproofing barrier system with or without a wearing surface.

Concrete Overlays

The effects of increased dead loading on the structure and reduced clearance must be considered when concrete overlays are specified. While four general types of concrete overlays have been used, most field experience has been based on the use of so-called low-slump, high-density concrete (LSDC) and latex modified concrete (LMC).

LSDC concrete achieves its reduced permeability through very low water cement ratios and a high degree of consolidation. It requires special finishing equipment. A bonding agent is applied to the original concrete surface prior to placement. The mix design typically has a water cement ratio of about 0.30, a high cement content of over 470 kg/m^3, and a slump less than 25 mm. Wet curing is required for at least 72 hours after placement.

LMC concrete consists of conventional concrete mixes with the addition of a polymeric latex emulsion of about 15 % latex solids by weight of concrete. The emulsion serves to reduce permeability and provide good bonding characteristics. LMC concrete typically requires less thickness than LSDC concrete, hence has weight advantages. The base concrete must be prewetted prior to application in order to minimize the absorption of water in the bonding grout by the base concrete which can lead to reduced bonding between the base and the patch material. Moist curing is required for 24 hours to properly hydrate the cement, and is to be followed by 72 hours of dry curing to develop the film forming qualities of latex.

Conventional concrete mixes with low water cement ratios have also been used; although costs are typically lower than LSDC and LMC overlays, durability typically is not as good and permeability is increased. Polymer concrete overlays containing polymers or epoxy additives have seen some application. Their limited use to date restricts the availability of long term performance information needed for evaluations.

Waterproofing Systems

Waterproofing systems fall into the general categories of membrane systems and sealers. Membrane systems function by providing an impervious barrier to the concrete surface. Sealers reduce penetration by filling the concrete pores below the level of the concrete surface.

Because of the wide range of sealers and membrane systems on the market and the absence of standard tests verifying penetration and durability performance, it is difficult to specifically state advantages and disadvantages of the various products.

Typically sealers require periodic reapplication at intervals ranging from one to five years. They cannot be used to fill surface penetrations in concrete such as cracks. Various types of sealer compounds include: boiled linseed oil, silicone, chlorinated rubber, epoxies and urethanes. An extensive laboratory test program sponsored by the National Cooperative Highway Research Program tried to evaluate the performance of a wide range of generically different sealers. The results are published in the report "Concrete Sealers for Protection of Bridge Structures," NCHRP report no. 244, available from the Transportation Research Board, Washington. The test program firstly established sealers which were successful in reducing chloride intrusion into concrete. Those which proved effective in reducing chloride intrusion were further tested to monitor chloride reduction rates under variations in concrete moisture content, coverage rates and simulated long-term weathering conditions. The test program determined a highly variable performance for the sealers tested. However, those which proved effective in reducing chloride intake into concrete were effective through the range of laboratory tests carried out.

Membrane systems have generally performed better in garage repairs than sealers, typically providing greater durability and resistance to chloride penetration. They are, however, generally more expensive. Two types of membrane systems are available: so-called "thin" membrane and "thick" membrane systems. Thin membrane systems typically consist of a rubber membrane about 1 mm thick and an epoxy or rubber wearing

course approximately 0.5 mm thick in which silica sand is embedded. They may be supplied in manufactured sheets, however, field experience with liquid applied materials has been more satisfactory. Thick membrane systems typically consist of hot or cold applied rubberized asphalt (3-4 mm thick) covered with a mastic asphalt wearing course (15-25 mm thick). The mastic asphalt, being waterproof, provides an additional degree of protection. The thickness can be varied to ensure adequate slopes towards drains. Although thick membrane systems are typically less expensive than thin membrane systems, they cannot be used in areas with height limitations. Additionally, thick membrane systems are susceptible to attack by oil and gasoline and when membrane systems wear out due to traffic abrasion, removal during preparation for replacement can be very difficult. In general, membrane field performance has been found to be highly dependent on installation procedures. Concrete surfaces must be dry, free from contaminants such as oil and previously applied membranes, otherwise blistering may occur. Blistering results from the expansion of entrapped gases, solvents and moisture; in certain instances blistering may require the complete removal of a recently applied membrane. Specific product information can be obtained from manufacturers. General guidelines on barrier systems for concrete can be found in the publication "A Guide to the Use of Waterproofing, Dampproofing, Protective and Decorative Barrier Systems for Concrete" ACI 515.1R-79, published by the American Concrete Institute.

4.5.5 Cathodic Protection

Cathodic protection systems began to be used on bridge structures about 10 years ago. Because the corrosion induced deterioration problems are similar to those encountered in parking structures, the technology has been applied to parking structures. Although initial installation costs are high, cathodic protection represents a method which potentially can prevent corrosion after repairs.

Corrosion occurs in regions where current leaves the metal called the anode. The principle behind cathodic protection is to reverse the flow of current using an externally applied source so that the electron flow is always directed into the reinforcement. This is accomplished by connecting reinforcement to the negative terminal of a D.C. power source and embedding a positively charged electrical network close to the level of the reinforcement in the concrete cover. Commercially available systems consist of strands of platinum or carbon wire either embedded in an overlay or slots cut in the concrete surface. Conductive polymer mesh systems have also been developed as well as conductive paint applied to the underside of the slab. Power is generally supplied by a transformer and rectifier system which converts 110 volt alternating current to a low voltage

direct current. Required power levels can be controlled either by feedback systems which use reference electrodes set in the concrete or by monitoring corrosion probes buried in the concrete. Power consumption is generally low, typically less than 10 watts per 100 m^2. Because cathodic protection does not prevent water seepage through the concrete, a barrier system is also required. The technology of cathodic protection for parking garages is still relatively new, hence maintenance costs and effectiveness have yet to be established.

4.6 Performance Evaluation of Repair Methods

Repair measures should not be expected to last the life of a structure. The 1984 survey attempted to evaluate the effectiveness of various repair measures by monitoring deterioration rates since repairs on a number of structures. Deterioration subsequent to repairs was measured using delamination surveys and corrosion activity. Table 3 summarizes generic descriptions of the protective systems. Table 4 presents the results of the survey. Descriptions of the types of structures surveyed are given in the 1984 survey. The results of the survey are based on a limited sample size and are confined to a monitoring period ranging from 2 to 6 years. The following conclusions were drawn from the survey:

- membrane barrier systems typically performed better than sealers. They provided substantially lower increases in delamination growth and corrosion activity

- it would be reasonable to expect about a 1 % delamination growth per year after repairs and application of a good quality membrane. This value represents approximately one quarter of the amount of deterioration which would be expected without repairs

- the use of a membrane waterproofing system was felt to be a cost-effective approach to rehabilitation.

4.7 Photographic Review

Figs. 12 to 18 present a photographic summary of typical parking structure deterioration, field investigation techniques and restoration measures.

5.0 INSPECTION/MAINTENANCE PROCEDURES

Due to their specialized functional requirements and the demanding environmental conditions under which they must perform, parking garages require periodic inspection and

Table 3 Generic Description of Waterproofing Systems from the 1984 CMHC Survey[12]

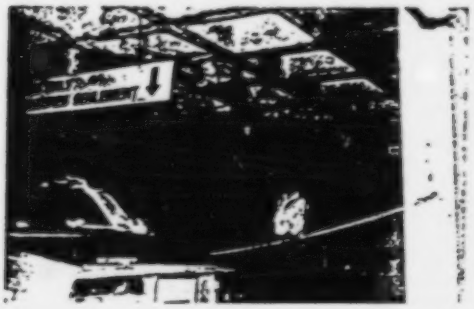
Product Identification	Generic Description
W-1	Applied-in-place, short, alkali-resistant glass fibre reinforced cementitious topping.
W-2	Applied-in-place, rubberized-asphalt waterproofing membrane with a divorcing sheet and a mastic asphalt wearing course.
W-3	Applied-in-place, latex-neoprene waterproofing membrane with a coal tar epoxy wearing course.
W-4	Applied-in-place, two-component polyurethane waterproofing membrane with a polyurethane and sand mix wearing course.
W-5	Applied-in-place, coal-tar-epoxy waterproofing system reinforced with a fibreglass sheet and surfaced with silica sand.
W-6	Applied-in-place, rubberized-asphalt polymer waterproofing membrane with a latex-rubberized-asphalt wearing course.
I-1	Applied-in-place, cementitious waterproofing system, containing catalytic chemicals and treated quartz.
S-1	Applied-in-place, two-component, solvent-based solution of flexible epoxy resin.

Table 4 Performance Evaluation Results of Various Repair Schemes [13]

Project	Age (Years)	Protective System	Damage (Percentage of slab delaminated) since repair	Time Since Repairs (Years)	Corrosion Activity
c1	13	W-3 (negligible permeability)	4.6	3	No active corrosion.
c2	16	W-4 over epoxy (nil permeability)	0.2	5	No active corrosion.
c3	26	Various	17.4	6	Active in 2.8 % of area
c4	13	I-1 in cracks	N.A.	2	N.A.
c5	9	W-1 (low permeability)	1.0	2	28% active
c6	15	Sealer	80	2-3	42.1 % active
c7	26	Asphalt	39.4	3	35.2% active
c8	9	W-2	1.8	5	1.7% active
c9	7	W-5 (nil permeability)	0.8	5	No active corrosion.
c10	21	W-3 on asphalt on epoxy	6.6	2	No active corrosion.
c11	10	S-1	37.7*	4-5	Not tested
Private Project	9	W-3	8.3	3	2.3% active

* % of repaired areas delaminated since report

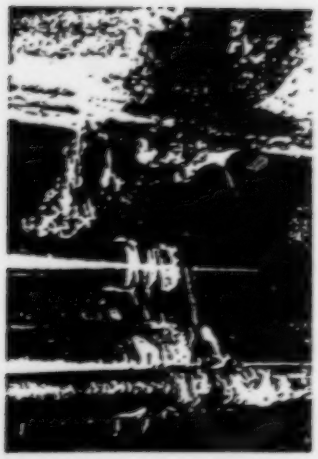
Extensive deposits of road salts on slab surface



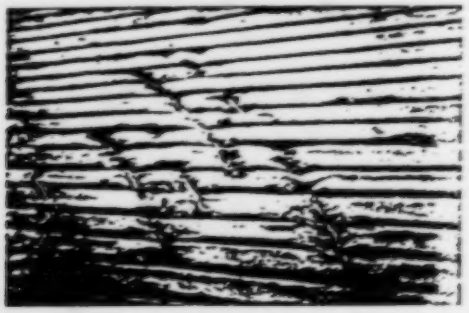
Closed parking area due to deterioration

Detail showing spalled concrete, corroded reinforcing steel and leaching deposits

Fig. 12 Intrusion of road salts and resulting deterioration to underside of floor slab.

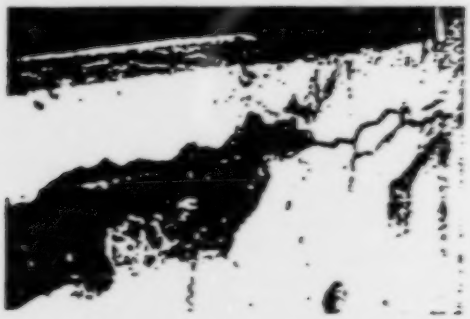


Severe leaching at underside of slab and leaching deposits on mechanical services



V-shape spalls on a ramp area. Note reduced concrete cover due to traction grooves

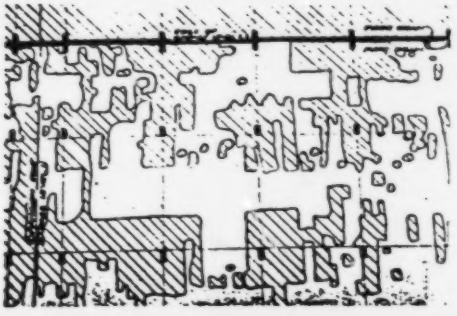
Spall at underside of floor slab and corroded reinforcing bar



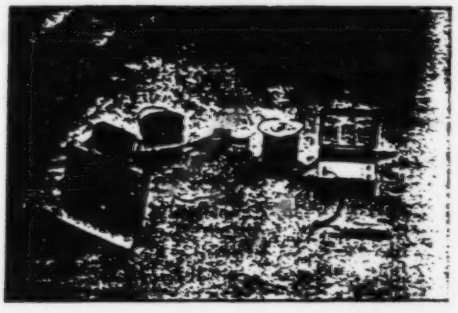
Detail of spall at ledge beam

Fig. 13 Typical examples of parking structure deterioration.

Chain-drag method used to determine delaminated areas



Delaminated areas shown shaded on floor plan



Half-cell test equipment used to measure corrosion activity (left)

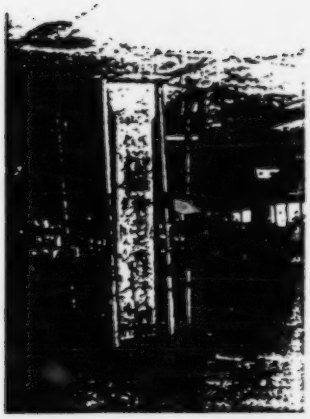
Pachometer used to measure concrete cover (right)

Half-cell test

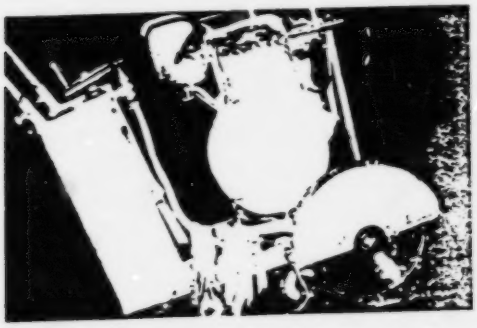
Pachometer test

Half-cell test and pachometer equipment being demonstrated

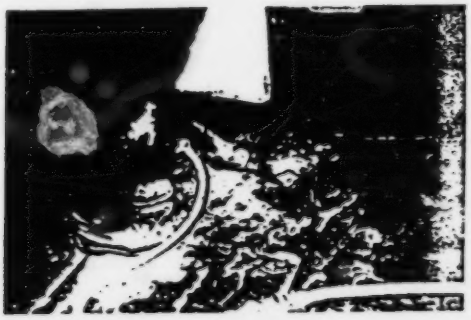
Fig. 14 Testing procedures forming part of condition survey.



Slab area shored in column capital area prior to chipping

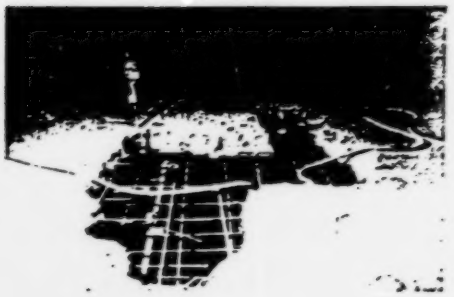


Concrete saw used to cut boundaries for regions to be chipped

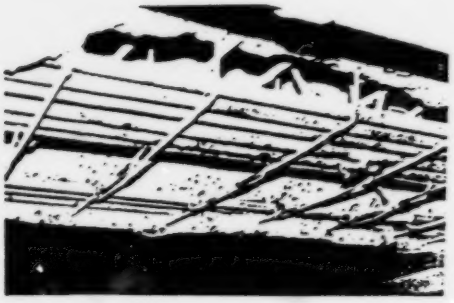


Concrete chipping using a jackhammer

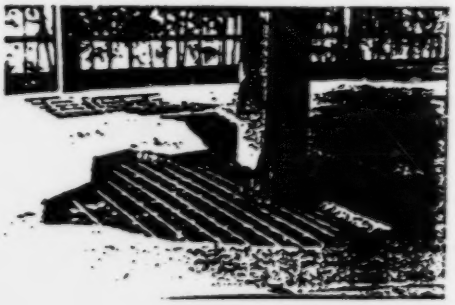
Fig. 15 Preparation of floor slab for remedial work.



Concrete chipping completely penetrating a floor slab



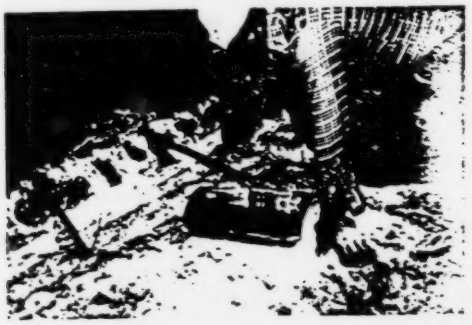
Exposed steel on a reinforced beam which exhibited extensive concrete deterioration



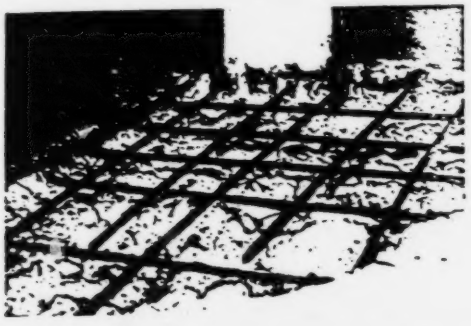
Overview of floor slab chipping

Fig. 16 Extensive chipping required to completely expose corroded reinforcement

Sandblasting exposed reinforcement



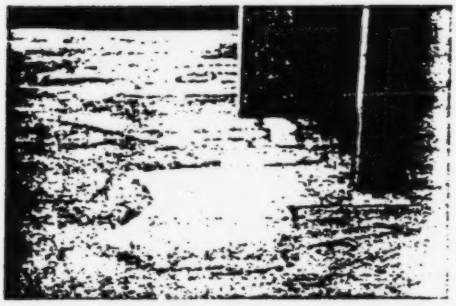
Epoxy coating sandblasted steel



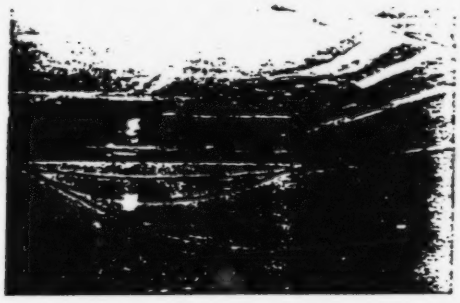
Steel reinforcement completely covered with epoxy paint

Drilling dowel holes to anchor replacement steel

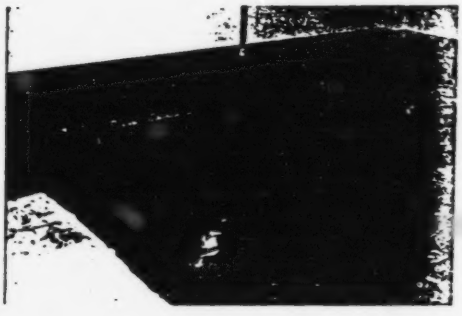
Fig. 17 Continuing remedial measures.



Overview showing patched areas



Underside of slab showing patched area



Epoxy waterproof membrane in place

Fig. 18 Final stages of repair measures.

maintenance procedures which recognize their special status as structures. Parking garages can be viewed as a hybrid between bridge structures and building structures, both of which require their particular inspection and maintenance approaches. In attempting to define inspection and maintenance requirements for parking structures, it should be noted that the history of modern multi-level underground reinforced concrete garages is rather a short one and the history of repaired structures is even more recent. Rehabilitation work incorporates new materials and new technologies which have yet to stand the test of time. This means that any inspection and maintenance procedures must entail a reasonable degree of conservatism so that future serviceability problems cannot enlarge to the degree of damage found on many of today's structures.

Based on current knowledge, the following inspection and maintenance procedures are recommended:

- an annual inspection should be carried out by a qualified professional. Particular attention is to be paid to the condition of any barrier system, if in place. Where the barrier system consists of a sealer or membrane on the slab surface, visual inspection is relatively easy. Where membranes are covered by a separated wearing surface, membrane damage is not readily apparent; however, inspection for leaks at the underside of the floor will give an indication of initial membrane distress.

- a regular maintenance program should be carried out by the owner. As part of this program, drains are to be inspected, cleaned and maintained in good working order; floor surfaces are to be flushed with water; adequate ventilation is to be maintained. Reference 1 "Parking Garage Maintenance Manual" provides detailed typical parking structure maintenance procedures together with recommended frequencies of maintenance practices. Conditions of particular structures should also be recognized such as high traffic areas and regions susceptible to high humidity. Two additional points can be noted: firstly, removal or significant reduction in heating can prolong floor life and secondly, storage of salt or salt/sand mixtures on garage floors is to be avoided.

6.0 ECONOMIC ISSUES

6.1 Overview

The costs associated with parking structure deterioration and subsequent repair measures are highly variable, depending on a large number of factors including:

- The nature and extent of deterioration. The nature of deterioration will affect such items as the corrosion activity, the relative penetration of leach deposits floor to floor and the structural implications of corrosion and spalling. The extent of deterioration will control the amount of concrete and reinforcement which must be removed and replaced.

- Structural details such as the dependence of the remainder of the building on the structural integrity of the parking garage, slab thickness, and slab type.

- Garage configuration. Repair costs will be directly dependent on parking structure size, the intricacy of the ramp systems, column spacings, and number of parking levels.

- Functional details such as the presence of embedded or suspended mechanical and electrical systems, slope adjustment requirements, repair access, hours of operation for repairs, surface finish requirements.

- Assessment of future service life of the structure. Some older garages may not justify extensive repair measures, while newer structures which may be badly deteriorated could warrant an extensive repair program in order to maintain required service life.

- Financing of repairs such as current interest rates, source of financing and lost revenue during rehabilitation from both parking charges and relocation costs for displaced parking spaces.

- Assessment of long-term performance of various barrier systems. Most barrier systems have been in place less than 10 years, hence limited field performance results are available.

In view of the many factors involved, it is difficult to establish specific principles which can be applied to a broad range of repair cases to arrive at the most cost-effective repair solution. The 1984 survey did, however, determine some guidelines which have been found to lower

overall costs of repairs to parking structures. These are:

- garage repairs carried out to high standards tend to be cheaper in the long run than the use of less desirable but initially cheaper repair methods

- funds spent on detection and repairs early in the service life of the structure will keep the repair costs significantly lower than delaying repair measures until extensive damage has occurred.

Parking structure repairs will generally involve a compromise between what is technically possible and what is economically feasible. For example, it is desirable that all chloride-contaminated concrete be removed during a rehabilitation program before the installation of a waterproofing membrane. Even though the majority of concrete may have chloride levels exceeding the threshold value for corrosion, this concrete may generally be sound and complete removal of all concrete would not be justified economically. Various approaches to the solution of this type of problem have been attempted. Manning and Ryell in Transportation Research Record No. 762 published in 1980 have developed a decision matrix for various possible bridge deck rehabilitation options[14]. Because of the many variables in parking structure repair, it would be difficult to adapt such a system to parking structures. Generally, the approach taken is to use the results of a condition survey, to quantify the magnitude of the problem and cost various repair options. This approach depends heavily on engineering judgment and experience.

6.2 Cost Estimates

Cost estimates for repair options require assessment of unit cost prices for specific items such as concrete removal and overlay systems and an assessment of the long term cost consequences of a repair strategy. Table 5 lists various typical unit costs for repair items. This has been developed from CMHC data for mean bid prices for competitive tenders received in Ontario in 1984.

Long term cost comparisons can be developed using a life cycle cost analysis technique. This cost forecasting tool reduces future costs, influenced by inflation and interest rates, to present value dollars, and hence comparisons of various options considering long term costs can be made. Three life-cycle repair strategy examples are presented in Figs. 19, 20, and 21. Figs. 19 and 20 detail the cases of repaired structures treated with a sealer assumed to have a 2-year and 3-year service life respectively. Fig. 21 details the case of a repaired structure having a high quality membrane system with an assumed service life of 10 years. Life-cycle cost analysis for parking structures requires a

Table 5 CMHC Mean Bid Prices for Tenders Received in Ontario in 1984

Repair Item	Unit Cost $
1. Asphaltic Concrete Removal (102 mm)	7.17/m^2
2. Asphaltic Concrete Removal (hand)	17.34/m^2
3. Asphaltic Concrete Placement (64 mm)	10.18/m^2
4. Concrete Removal & Replacement (25mm)	86.49/m^2
5. Concrete Removal & Replacement (77 mm) Roof	95.44/m^2
6. Concrete Removal & Replacement (77 mm) Interior	98.35/m^2
7. Through Slab Concrete Replacement	264.46/m^2
8. Underside Repairs (Ledge Beam & Columns)	305.89/m^2
9. Waterproofing & Wearing Course	
Duronite	27.40/m^2
Vulcan	20.85/m^2
Rubberoad	23.90/m^2
10. Drains	
E 1830	664.00/ea
E 1400	450.00/ea
11. Crack Injection	113.26/m
12. Cathodic Protection	85.79/m^2
13. Latex Modified Overlay	38.00/m^2
Joints (for crack control)	6.42/m
14. Concrete Topping	23.85/m^2
Joints (for crack control)	9.14/m

Assumptions:
- no initial protection
- major repair in year 6
- application of high quality sealer
- 2-year life expectancy for sealer
- periodic slab repairs in years 12, 18,24,30,36
- discount rate 11%, escalation rate 5%

	PRESENT VALUE $
1. Capital Costs	
10 000 m^2 x $82.00 x 0.716	587 120
2. Maintenance Costs	
Annual maintenance costs years 6 to 40	
10 000 m^2 x $1.10 x (14.837 x 0.716)	116 856
3. Cyclical Renewal	
a) Clean slabs and reapply sealer (yr. 2,4,6,8, etc.)	
10 000 m^2 x $9.15 x 7.494	685 701
b) Periodic repairs (yr. 12,18,24,30,36 etc.)	
10 000 m^2 x $36.50 x 1.47	536 550
c) Minor parking disruption costs (yr. 2,4,8,10,14, 16,20,22,26,28,32,34,38)	
300 x $12.00 x 5.308	19 109
d) Major parking disruptions during cyclical repairs (yr. 6,12,18,24,30,36)	
300 x $50.00 x 2.186	32 790
TOTAL PRESENT VALUE THIS OPTION	$ 1 978 126

Fig. 19 Life cycle cost analysis - structure protected with sealer having 2-year service life

Assumptions:
- no initial protection
- major repair in year 6
- application of high quality sealer
- 3-year life expectancy for sealer
- periodic slab repairs in years 12, 18,24,30,36
- discount rate 11%, escalation rate 5%

	PRESENT VALUE $
1. Capital Costs	
10 000 m^2 x $82.00 x 0.716	587 120
2. Maintenance Costs	
Annual maintenance costs years 6 to 40	
10 000 m^2 x $1.10 x (14.837 x 0.716)	116 856
3. Cyclical Renewal	
a) Clean suspended slabs, reapply sealer (yr. 3,6, 9,12 etc.)	
10 000 m^2 x $9.15 x 4.888	447 252
b) Periodic repairs (yr. 12,18,24,30,36 etc.)	
10 000 m^2 x $36.50 x 1.47	536 550
c) Minor parking disruption costs (yr. 3,9,15,21, 27,33,39)	
300 x $12.00 x 2.702	9 727
d) Major parking disruption costs (yr. 6,12,18,24, 30,36)	
300 x $50.00 x 2.186	32 790
TOTAL PRESENT VALUE THIS OPTION	$ 1 730 295

Fig. 20 Life cycle cost analysis - structure protected with sealer having 3-year service life

Assumptions:
- no initial protection
- major repair in year 5
- application of membrane, wearing course
- 10-year life span for wearing course
- discount rate 11%, escalation rate 5%

	PRESENT VALUE $
1. Capital Costs	
10 000 m^2 x $110.00 x 0.757	832 700
2. Maintenance Costs	
Annual maintenance costs years 6 to 40	
10 000 m^2 x $1.10 x 11.353	124 883
3. Cyclical Renewal	
a) Removal and reapplication of wearing course any associated membrane repairs years 15,25,35	
10 000 m^2 x $55.00 x 0.827	459 850
b) Parking disruption revenue losses years 5,15, 25,35	
300 x $50.00 x 1.584	23 760
TOTAL PRESENT VALUE THIS OPTION	$ 1 436 193

Fig. 21 Life cycle cost analysis - structure protected with membrane system having 10-year service life

number of assumptions to be made. Some, such as future financing costs and service performance limits, which can have a significant impact on total costs are difficult to predict. Barrier system performance has limited long-term field testing. Other assumptions such as initial capital costs can be estimated to a higher degree of confidence if they are based on the results of accurate condition surveys and current interest rates. The relative influence of given assumptions can be examined by considering a range of possible financing charges and/or barrier system service life capabilities for a given parking structure. The following assumptions have been used in developing the life-cycle costs of Figs. 19 to 21:

- area of suspended floor slab — 10 000 m^2
- functional life of the garage — 40 years
- garage capacity — 300 cars
- monthly parking fee — $ 50.00
- discount rate — 11 %
- escalation rate — 5 %
- assume 10% of surface area shows signs of delamination when major repairs are required (year 6 for the sealer examples and year 5 for the membrane example)
- assume an annual maintenance program consisting of periodic slab washdown and minor repairs to wearing surface in high traffic areas — $ 1.10/ m^2
- for membrane system, assume function life of 10 years
- for sealers, assume function life to be 2 or 3 years (both cases considered)
- assume 2% annual delamination for concrete protected by sealers, 1% annual delamination for concrete protected by membrane systems.

While the membrane protected structure exhibits the lowest life-cycle cost for the three examples, the repair costs of each deteriorated structure must be carefully assessed according to the best available information on repair performance data, material costs and other factors which apply at a given time and in the particular location of the structure. Life cycle costs are very difficult to predict over a typical 40 to 50 year service life and prudent

engineering practice should point towards measures which would be most effective in delaying active corrosion.

Concerning inspection and maintenance for repaired garages, limited experience indicates that about 0.5% to 2% of the value of the structure should be budgeted annually towards such expenses. Assuming a typical 1985 construction cost of \$ 320/m^2 for a reinforced concrete underground parking garage, annual inspection and maintenance costs will be of the order of \$ 1.60 to \$ 6.40/m^2.

APPENDIX A

A Chronological Ordering of Events Related to the Deterioration of Parking Garages

A Chronological Ordering of Events Related to the Deterioration of Parking Garages

July, 1977: An Early Paper

"Design Durable Maintenance-Free Prestressed Concrete Parking Structures", H.C. Walker, Concrete Construction.

March, 1980: Complete Journal Issue on Parking Garages

For the first time, a widely read technical journal devoted a complete issue to the design and repair of parking garages: Concrete International, Design and Construction, V.2, No. 3, March 1980.

August, 1981: First Set of Guidelines

"Investigation, Repairs, Design and Construction of Parking Structures". This interim guideline was developed by the Committee on Parking Structures, ACI Ontario Chapter. It covers condition surveys and repair procedures for deteriorated garages.

September, 1981: an Early Conference

American Concrete Institute Fall Convention, Quebec City.

Later conferences on parking garages were:

- September, 1982: National Association of Corrosion Engineers, seminar held in Chicago, Illinois.
- October, 1984: One Day Workshop on Concrete Failures and Deterioration and Rehabilitation of Parking Garages, Ottawa, Ontario.
- May, 1985: International Workshop on Alkali-Aggregate Reactions in Concrete and Construction and Rehabilitation of Concrete Parking Structures, Montreal, Quebec.
- October, 1985: Learning From Experience/Avoiding Failures, Fourth Canadian Building Congress, Ottawa, Ontario.

November, 1981: CMHC Report

CMHC commissioned a visual survey of 84 parking structures attached to apartment buildings in the Ottawa area. It subsequently published the results in a report entitled "The Nature, Extent and Impact of Residential Parking Structures' Deterioration" in November, 1981. This was the first survey of its kind in Canada.

1982: Ontario Housing Corporation Survey

This was a visual survey of 159 parking garages in Ontario. OHC rated the garages from 1 (no significant deterioration) to 10 (extremely advanced state of deterioration).

May, 1982: CSA Steering Committee Meeting

A task force was established to determine the terms of reference for a Technical Committee that would be formed to prepare a CSA Standard for durable parking structures. The task force was chaired by K.H. Thompson of Public Works Canada.

July, 1982: First NRC Publication

"Deterioration of Indoor Parking Structures", G.G. Litvan, CBD 224, National Research Council of Canada.

1982: Maintenance Manual

"Parking Garage Maintenance Manual", published by the Parking Consultants Council of the National Parking Association (US). This manual covered the cleaning and maintenance procedures that were considered essential for preventing the premature deterioration of garages.

December, 1984: CMHC Survey

Trow Ltd. was commissioned in 1983/4 by CMHC,NRC,PWC and DSS to survey garages in Montreal, Toronto, Ottawa, and also a small number of garages in the Maritimes.

Spring, 1983: Formation of CSA Technical Committee

This committee was formed to draft CSA Standard S413M, "Durable Parking Structures". Its first meeting was in October, 1983. The Standard, which is expected to be available by May, 1986, will cover the design of new parking garages. No steps have been taken at this time to draft a Standard on repair of existing garages.

September, 1984: Technical Builders' Bulletin, CMHC

Design requirements for all new housing with parking garages for which NHA commitments are made after October, 1984.

March, 1985: Association Formed to Represent the Repair Industry

Nine Toronto contractors joined together to represent the new industry. They will be soliciting members from coast to coast from contracting firms that specialize in the repair of parking garages.

Code Development in the United States

The following two state-of-the-art papers dealing with parking structure deterioration have been recently published in the Journal of the American Concrete Institute:

- "Corrosion of Metals in Concrete"[3], January - February, 1985
- "State-of-the-Art Report on Parking Structures"[15], July - August, 1985

A code of practice covering the investigation and repair of existing garages and the design of new garages is expected by 1988-89.

APPENDIX B

Checklist for a Parking Structure Condition Survey

Summary of Information on Plans and Specifications for Parking Structures

A. General Information

1. Name and address of building:

   _____
   _____
   _____

2. Date of last revision on plans: _____

3. Parking spaces. Roof: _____ Underground: _____

4. Type of structure: (flat plate/flat slab with drops/ 1-way slab/prestressed/structural steel) (circle one)

5. Above ground or below ground. Enclosed or open.

6. Heated or unheated.

7. Seperate structure or part of building.

8. Number of levels, excluding roof: _____

B. Design Data

1. On seperate sheets of paper, show:

   - plan of typical floor with grid lines, dimensions, etc.
   - expansion joint locations
   - expansion joint details
   - floor drain detail
   - section through structure

   Note: if there is a waterproof membrane, show treatment at drains and expansion joints.

2. Concrete:

   Class of exposure specified: A B C D
   (Circle one - refer to Table 7 in CSA Standard CAN3-A23.1-M77, "Concrete Materials and Methods of Concrete Construction".)

   Air entrainment: _____%

   Minimum cement content: _____ kg/m3

   28 day strength: _____ MPa

3. Specified cover: _____ mm

4. Waterproofing/sealer specified?

   Type: _____

5. Epoxy coated bars? _____

6. Slope to drains: _____ %

7. Spacing between drains: _____ metres

Checklist for Expert Walkthrough of Parking Structures

A. General Information

1. Name and address of building:

   _____
   _____
   _____

2. Building manager's name and telephone number:

   _____
   _____

3. Type of construction: _____

4. Repair history: _____
   _____
   _____

5. Inspected by: _____

6. Date: _____

B. Summary of Ratings

Note: This section to be completed after sections C and D.

(Use: very poor/poor/fair/good/very good)

	Topside Visual	Underside Visual	Over-all Rating
Roof Slab	_____	_____	_____
Interior Slabs	_____	_____	_____
Ramps	_____	_____	_____
Expansion Joints			_____
Walls, columns			_____
Other: _____			_____

Overall Parking Structure Rating: _____

Comments regarding serious structural defects: _____

C. Slab-on-Grade Suspended Floor Ramp Roof Slab
(circle one)

Note: make as many photocopies of this section as required.

1. Level: _____

2. Top Surface

(a) Type of Protection: membrane sealer none
(circle one)

(b) Membrane

Description: _____

Condition: _____ worn in high traffic areas

_____ de-bonded from concrete

_____ torn or cracked

(c) Sealer

Evidence of re-sealing? _____

If water is poured on the concrete, does it form droplets? _____ Does it soak in? _____

(d) Patches and Potholes

_____ None

_____ Some

_____ Many

_____ Numerous

(e) Cracks in the Surface

(i) Amount of Cracks

_____ None

_____ Few (1 m long per 20 m2)

_____ Many (1 - 5 m long per 20 m2)

_____ Numerous (more than 5 m long per 20 m2)

(ii) Crack Widths

_____ Barely Visible

_____ Easily Visible

_____ 0.5 mm or less

_____ more than 0.5 mm

(f) Concrete Delamination

_____% of area (estimated by random chain dragging)

(Note: with some membranes it may not be possible to distinguish between a de-bonded membrane and delaminated concrete.

(g) Maintenance

Are the floors swept clean? _____

Any signs of salt deposits? _____

(h) General Condition of Top Surface

_____ Very Good

_____ Good

_____ Fair

_____ Poor

_____ Very Poor

3. Underside

(a) Cracks Associated with Leached Deposits/Rust Stains

_____ None

_____ Few (1 m long per 20 m2)

_____ Many (1 - 5 m long per 20 m2)

_____ Numerous (more than 5 m long per 20 m2)

(b) Concrete Spalls - Amount of Spalling

_____ None

_____ Few (1 % of total area)

_____ Moderate (1 - 2 % of total area)

_____ Numerous (more than 2 % of total area)

(c) Exposed Reinforcing Bars

(i) Amount of Exposed Bars	(ii) Condition of Bars
_____ None	_____ Unrusted
_____ Few	_____ Slightly Rusted
_____ Many	_____ Moderately Rusted
_____ Numerous	_____ Severely Rusted

(d) Wet Spots

_____ None

_____ Few

_____ Many

_____ Numerous

Do these spots correspond to locations of ponded water on the top surface? _____

(e) General Condition of Underside

_____ Very Good

_____ Good

_____ Fair

_____ Poor

_____ Very Poor

D. Other Components

(Use: none/few/some/many/numerous)

1. Expansion Joints (floors and roof)

Leakage _____

Cracking/seperation from concrete _____

Rust staining _____

Adjacent spalling _____

Adjacent exposed bars _____

Expansion joint movement accomodated? yes no

2. Expansion Joints (columns and walls)

Cracking/seperation from concrete _____

Leakage _____

Rust staining _____

Adjacent spalling _____

Adjacent exposed bars _____

Expansion joint movement accomodated? yes no

3. Columns/Beams

Cracking _____

Spalling _____

Exposed bars _____

4. Walls

_____ Block/Poured Concrete (circle one)

Water staining _____

Spalling _____

Exposed bars _____

5. Drains

Drains _____ clean _____ clogged _____

Positioned properly? _____
(Are there large areas of ponded water without drains?)

Leakage around drain? _____

Leakage through headers? _____

Adjacent concrete deterioration? _____

REFERENCES

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7. Bickley, J.A., "Parking Structure Deterioration: A Survey and Analysis of its Extent and Influencing Factors" (unpublished), CMHC, December 1984, p. 31.

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11. Bickley, p. 19.

12. Bickley, p. 20.

13. Bickley, p. 69.

14. Manning, D.G., and Ryell, J., "Decision Criteria for the Rehabilitation of Concrete Bridge Decks," Transportation Research Record No. 762, Transportation Research Board, 1980, p. 7.

15. ACI Committee 362, "State-of-the-Art Report on Parking Structures," J. ACI, No. 4, Vol. 82, July-August, 1985, pp. 544-578.